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THE APPLICATION OF LASER SPECKLE INTERFEROMETRY TO MEASURE STRAIN AT ELEVATED TEMPERATURES AND VARIOUS LOADING RATES

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MATERIALS DYNAMICS BRANCH

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ABSTRACT

This report investigates the application of speckle interferometry for the measurement of strain when a material is subjected to various loading rates and elevated temperature conditions. The Medium Strain Rate Facility at the U.S. Army Materials Technology Laboratory was used to conduct uniaxial tension tests at strain rates of 10^{-5} sec^{-1} to 10^{-1} sec^{-1} , temperatures up to 250°F and heating rates of 250°F/sec . Strain was measured by laser speckle interferometry technique and strain gages, the results of both methods were compared. Laser speckle interferometry was also used for the measurement of strain at large deformation, i.e., necking region of tensile specimens. The laser speckle interferometry results are in agreement with strain gage results at strain rates up to 10^{-1} sec^{-1} and for temperatures up to 250°F . This investigation also indicated laser speckle interferometry would be an excellent noncontact localized strain measuring device for adverse conditions if the following drawbacks were overcome. When using the ruby laser system, only one stress-strain data point can be obtained, the present system is not suited for strain rates over 10^{-1} sec^{-1} and no results can be obtained if the specimen is heated to a point that it begins to emit intense red light. The shortcomings of laser speckle interferometry could be overcome by using another laser and data acquisition system.

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INTRODUCTION

This report investigates the application of speckle interferometry for the measurement of uniaxial strain when a material is subjected to various loading rates and elevated temperature conditions. There are many applications where a material is subjected to high strain rates, high heating rates, and large deformation, i.e., forging, ballistic impact, and penetration. To properly analyze and design systems, these conditions must be taken into consideration. Therefore, it is necessary to acquire material relationships under conditions of high temperature, high heating rates, and various loading rates to large strain. Measurement of large strain, when subjecting a material to strain rates greater than 0.01/sec and high temperatures has always posed severe limitations. Many investigators have developed contact and noncontact extensometers for measuring strain in hostile environments.¹ These extensometers are often limited in the strain rate and total strain they can measure. One noncontact method for measuring strain under quasi-static load conditions is the Laser Speckle Interferometry (LSI) technique.²⁻⁵ This optical technique of double exposure laser speckle photography is well established for measuring in-plane displacement. This technique has been applied to measure the transverse displacement of a cantilever beam following tip impact.⁶ For this investigation, a test plan was formulated to determine the feasibility of using LSI to make strain measurements between strain rates of 0.00001/sec and 0.01/sec and at high temperatures. In this study, the displacement field along the axial direction of a specimen subjected to high temperatures, high heating rates, and various loading rates was measured with LSI and strain gages. Load and temperature are recorded also, allowing the calculation of strain rate and stress-strain relationships. It will also be demonstrated that this method can be used to measure strain at large deformations, i.e., necking regions of tensile specimens.

EXPERIMENTAL APPARATUS AND PROCEDURE

The tests were carried out in the Medium Strain Rate Machine (MSRM) Facility at the U.S. Army Materials Technology Laboratory (MTL),⁷ which is shown in Figure 1. The machine has a 140,000 pounds static load capacity. There are two operating modes: closed loop mode and open loop mode. In the closed loop mode, the MSRM is the same as any hydraulic servo controlled test machine, a strain/load/displacement rate up to 1 sec⁻¹ can be achieved. In the open loop mode, the hydraulic fluid is replaced by nitrogen gas. A fast-acting valve, instead of the servo valve, is used to release the gas from the top or bottom of an actuating piston creating a pressure differential which moves the piston. The loading rate in the open loop mode is controlled by the gas pressure, stroke of the piston, and the orifice size selected in the fast-acting valve. A rate of 50 sec⁻¹ can be achieved depending on the ductility of the specimen. In this study, the effect of strain rate was investigated by testing specimens at three different strain rates; e.g., 10⁻⁵, 10⁻³, and approximately 10⁻¹ sec⁻¹. All tests were conducted in closed loop mode, and load, strain, temperature, and laser firing were monitored continuously through an automated data acquisition system which also controls the tests in closed loop mode.

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7. CHOU, S. C., GREEN, J. L., and SWANSON, R. A. *Mechanical Properties and Design Allowables of AS4(12K)/923 Graphite Epoxy Composite*. U.S. Army Materials Technology Laboratory, AMMRC SP 85-1, July 1985.

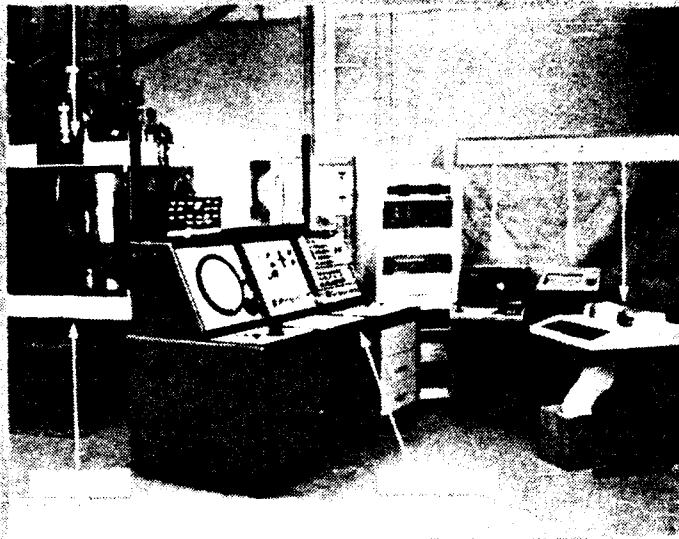


Figure 1. Automated materials characterization system.

The heating apparatus used for high temperature soak tests and high heating rate tests utilized the resistance heating technique. This method involves passing large amounts of current through the specimen using the specimen's resistance to convert the current to heat. The apparatus consists of a variac autotransformer, which is used to control the power output of the apparatus, a step down transformer for converting low current high voltage to high current low voltage, a high voltage relay, and welding cables for transmitting power to electrodes. The configuration of the test equipment is shown in Figure 2. The apparatus is powered by a 240V 60 amp AC line and is capable of outputting 11.5 volts, 1150 amps. The system is actuated by a computer controlled high voltage relay between the variac and the step down transformer.

In the step down transformer, voltage is reduced by a factor of 20.8 and the maximum output of the step down transformer is 11.5 volts. From the transformer, power is transmitted through four flexible 4/0 welding cables to electrodes in the specimen grips. Specimen heating rate is proportional to the energy dissipation rate. Assuming an ideal situation in which all energy is converted to heat, the heating rate can be estimated by:

$$\Delta T / \Delta t = V^2 / (ARmS) \quad (1)$$

- A = Conversion Factor
- V = Applied Voltage to Specimen (volts)
- R = Resistance of Specimens (ohms)
- S = Specific Heat of Specimen (BTU/lb °K)
- ΔT = Temperature Difference (°K)
- Δt = Duration of Heating (sec)
- m = Mass of Specimen (lb)

Since no real system is an ideal one, the estimated heating rate just provides a starting point from which the desired heating rate for a particular specimen geometry and material can be obtained by adjusting the voltage and measuring the temperature time history of specimens. This voltage is

then used on all subsequent tests at that heating rate. Variable heating rates up to 2000°F/sec are possible with the present apparatus, along with closed loop constant temperature control when used in conjunction with a computer.

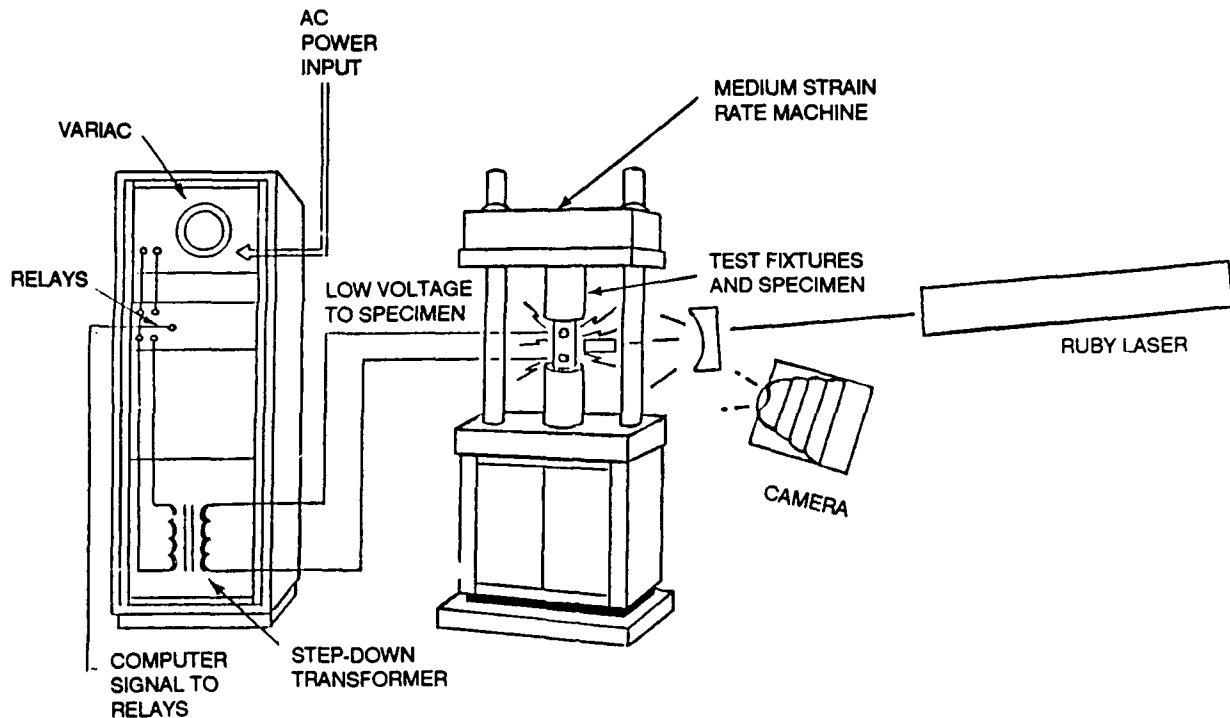


Figure 2. Loading, heating, and strain measuring apparatus.

Special attention must be paid to the design of the grip system because it requires being isolated electrically from the specimen, and must also be strong enough to sustain the load. Tapered aluminum oxide inserts were used to transmit load and provide insulation, both thermally and electrically. The complete grip assemblies are shown in Figures 3a and 3b. The inserts are machined to fit into split collar bushings and conform to the specimen's geometry. The specimen is inserted into the split collars, before the two split collars are assembled and threaded into the top and bottom cylindrical couplers. Copper electrodes are used as conductors, which are spring loaded to maintain contact with both ends of specimen at all times. Copper electrodes and springs are insulated from the cylindrical couplers with nylon bushings.

Laser speckle interferometry was used for making strain measurements. With the method of double exposure speckle photography, the displacement of a surface in a plane normal to the line of sight was measured. This is done by using a camera to record two superimposed images of the surface, one before and one after deformation. The optical set-up of Figure 2 shows the location of the camera and ruby laser with respect to the specimen. The laser beam from the pulsed ruby laser is expanded by using a concave lens. This allows the entire surface of the specimen facing the camera to be illuminated. The intensity of the pulse is sufficient to expose the film within its pulse width time of 30 nanoseconds, when in Q-switching mode, and generate the speckle pattern on the film. The natural reflectiveness of the metals tested helps to form a good speckle field.

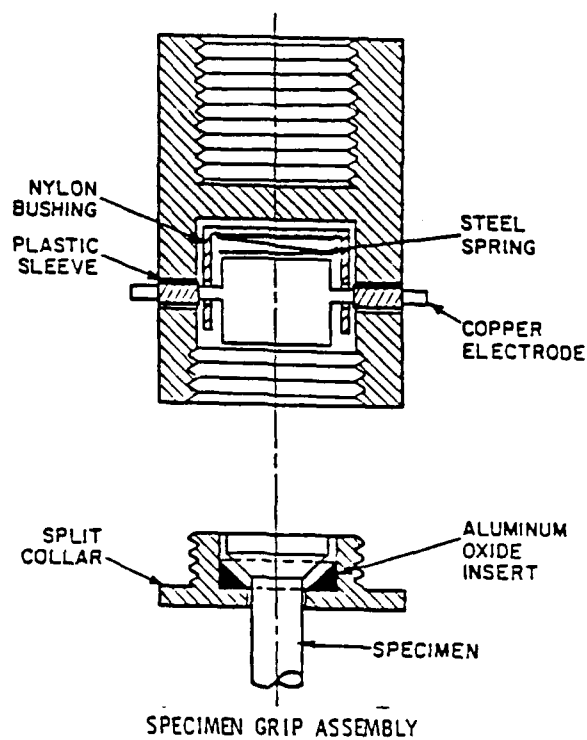


Figure 3a. High heating rate specimen and grip assembly.

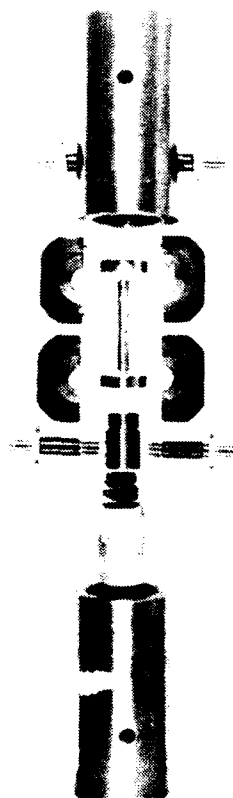


Figure 3b. High heating rate specimen and grips.

The pulsed ruby laser allows one to capture instants in dynamic experiments due to its short pulse time. If the movement of the objects' surface between the two exposures is larger than the diameter of the speckles recorded by the camera onto the film and if these speckles remain correlated with one another, then the image will scatter a beam of light into a diffraction halo. The intensity of the light in this halo varies periodically across the field yielding cosine square fringes. This is shown in Figure 4. These fringes will have an angular spacing, α , given by:

$$\sin \alpha = \lambda(M/D) \quad (2)$$

where λ is the wavelength of the readout beam, M is the demagnification of the image, and D is the surface displacement.^{3,4} The fringes are perpendicular to the direction of displacement.

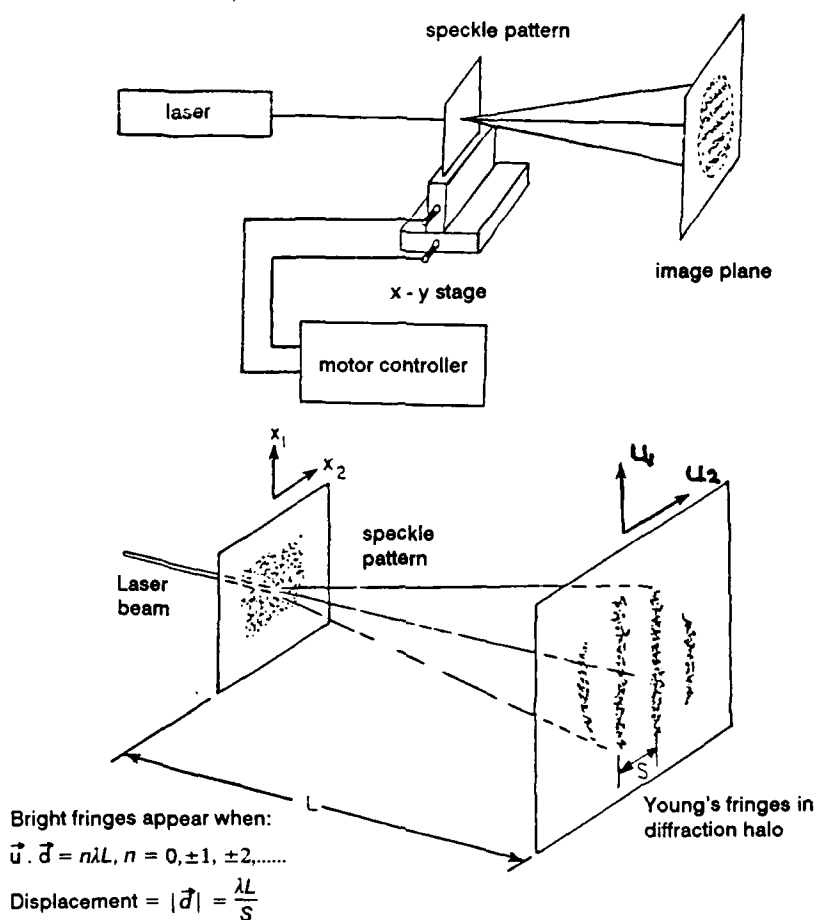


Figure 4. Measurement of in-plane displacement by laser speckle photography.

The speckle-grams are read by using a helium-neon laser to illuminate different points across the gage length of the specimen. The far field diffraction pattern is observed at a distance of 75.88cm from the speckle-gram. The following equation relates the angular spacing α to the number of bright fringes N , the measured distance S between dark fringes, and the distance L between speckle-gram and diffraction halo.

$$\sin \alpha = NL/S \quad (3)$$

By combining Equations 2 and 3, object displacement is obtained. The demagnification factor, m , drops out when strain is calculated due to the fact that the gage length used for calculating the strain is measured from the image on the film rather than from the specimen itself. The electrical schematic of the experimental set-up is shown in Figure 5. The first exposure is taken before loading the specimen and the second exposure is taken after a certain predetermined load level (unless otherwise noted). The load level is increased from 1,000 to 1,800 pounds, depending on the heating and loading conditions to allow for measurable strain data using laser speckle. These measurable strain values lie between 900 to 2,500 $\mu\epsilon$ for a particular speckle-gram. At values of strain less than 900 $\mu\epsilon$, displacement is not larger than the speckle diameter recorded with the camera aperture fully open and a demagnification = 1. Conversely, with these camera conditions, strains greater than 2,500 $\mu\epsilon$ causes decorrelation of the speckle pattern, making it impossible to interpret fringes.

Schematic of Test Setup

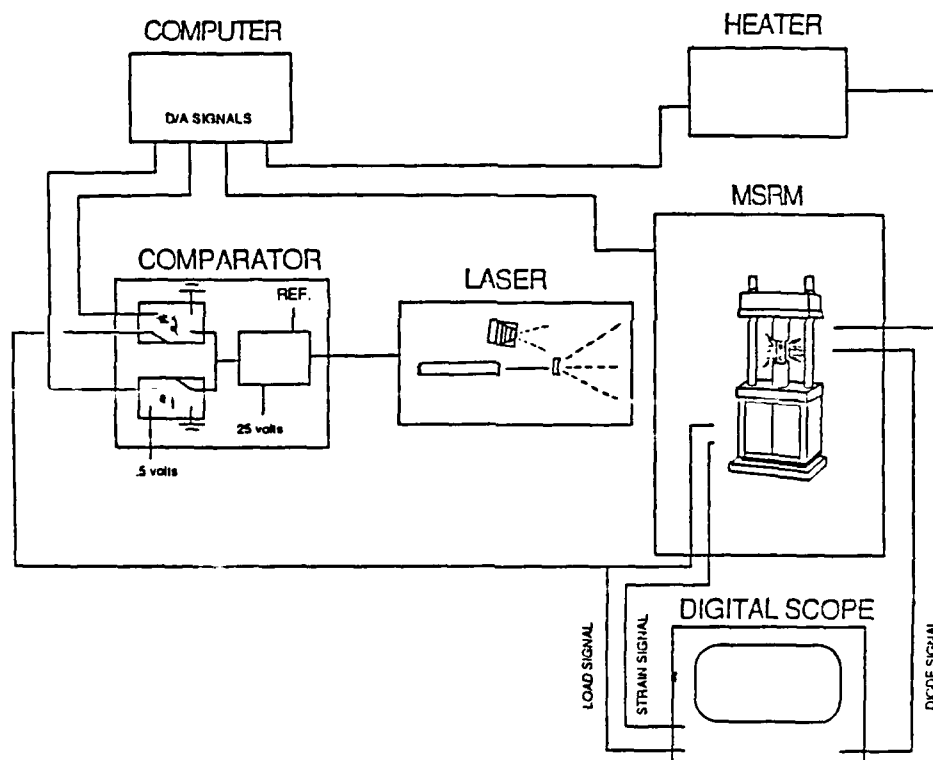


Figure 5. Electrical schematic of experimental set-up.

The high heating rate tests conducted involved sending large amounts of current through the specimen for one second, then the heater was turned off and loading of specimen began; this process was controlled by a computer via digital/analog (D/A) signals. The second exposure of film was accomplished by triggering the ruby laser at a specimen load level that would give a measurable strain. The triggering of the ruby laser for high heating rate tests was accomplished by electrically comparing the load signal to a preset reference voltage. This

allowed us to select any point along the load time history of specimen for firing the laser. An electric circuit was designed that would trigger the laser from the load signal and eliminate the large EMF picked up by the load signal during heating of specimen, thus premature triggering of the laser was eliminated. The circuit, as shown in Figure 5, was composed of a comparator and two relays. Relay #1 lets the comparator compare a nonzero voltage with the trigger voltage during heating. After heating, relay #2 shorts allowing the load signal to enter the comparator and relay #1 opens an instant later. The relays open and short by way of 10 volt pulses sent from the D/A channels of computer. Then another 0 to 10 volt ramp signal was sent from the computer to MSRM for controlling the loading of the specimen. Room temperature and soak tests do not require the two relays, a simple high speed comparator is used in these cases. To determine exactly when the laser fired, a high speed photodiode was used with a rise time of 12 picoseconds. By recording the output voltage from the load cell, strain gage, photodiode, and the thermocouple together with same time scale, the complete set of data was obtained for later analysis. The test conditions are listed in Table 1. There were two materials used in this study, 1215 steel and 5456 aluminum.

Table 1. TEST MATRIX

Material	ϵ	T	\dot{T}
1215 Steel	10^{-5}	RT	—
1215 Steel	10^{-5}	250°F	Soak
1215 Steel	10^{-3}	RT	—
1215 Steel	10^{-3}	250°F	Soak
1215 Steel	10^{-3}	250°F	250°F/sec
1215 Steel	10^{-1}	RT	—
1215 Steel	10^{-1}	250°F	Soak
1215 Steel	10^{-1}	250°F	250°F/sec

In addition to the test matrix, tests were conducted to answer specific questions about the application of laser speckle interferometry. The first question to be resolved was the applicability of laser speckle interferometry to the measurement of strain increments when a material has been subjected to large deformation. To answer this question, a specimen was strained to the point where necking of specimen was visible. Then LSI was used to measure further straining in the necking regions. The second question to be answered was whether LSI would work when a steel specimen was heated until it began to glow and then strained.

RESULTS

The speckle-grams generated from the double exposure LSI were analyzed and a typical plot of axial displacement versus gage length of the specimen is shown in Figure 6. Assuming a uniform strain field, the slope of these points is equal to the instantaneous strain. By monitoring the load at the time the laser fires, the stress and strain of the specimen at that instant can be obtained. By conducting a series of experiments on 1215 Steel at various strain rates and temperature conditions, a set of points is obtained which will provide the stress-strain history for the material. Because we were comparing the LSI strain readings to those of a strain gage, the specimen's maximum temperature was limited by the strain gage ($\approx 250^\circ\text{F}$). The maximum strain rate used for testing was $10^{-1}/\text{sec}$, this limit was due to the LSI system. The limits imposed by LSI system were due

to the slow response of the electrical circuit used for firing the ruby laser at a given load threshold. All 1215 Steel specimens were tested in the elastic range. Results of these tests are in Figures 7 through 18. Since all tests were conducted in elastic range, no strain rate effect would be noticed if one was present. However, an increase in scatter with increase in strain rate can be observed. This points out that the present laser equipment is not suited for testing at strain rates greater than 0.01/sec. The steel stress-strain results show good agreement between strain gage and LSI with less than 7% error. High temperatures and high heating rate tests conducted show no significant effect in steel, but Figure 8 shows a trend in decreasing moduli from RT to 250°F. The LSI was successfully used to measure strain at higher temperatures; but when the specimen began to visually glow red, no fringes were recorded. This indicates that LSI using a ruby laser cannot measure strain at extreme temperatures when the specimen is glowing.

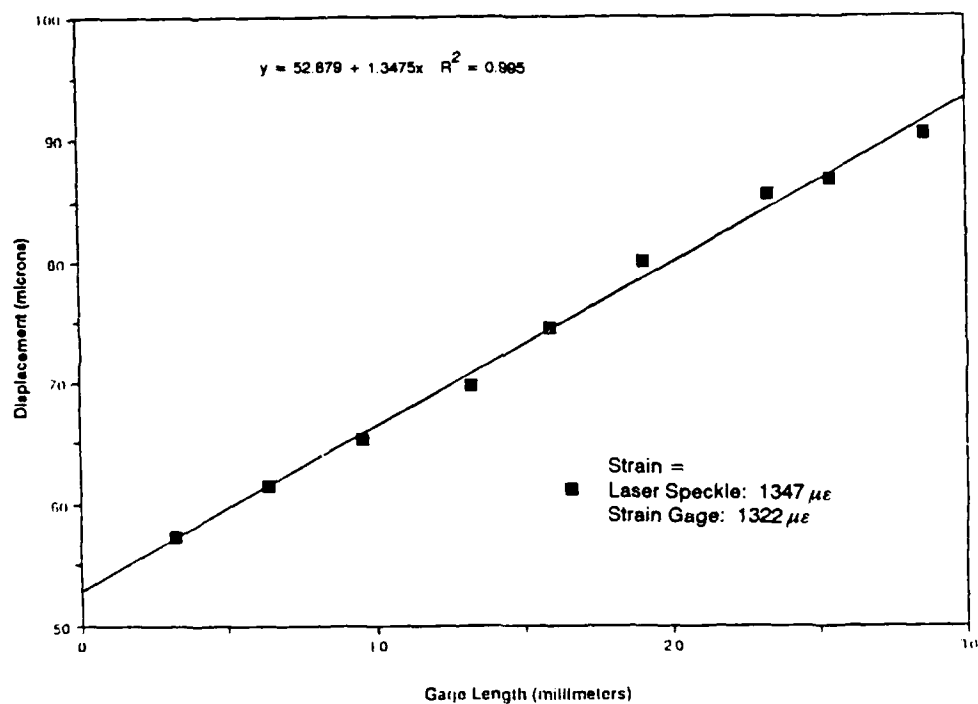


Figure 6. Typical displacement versus gage length plot.

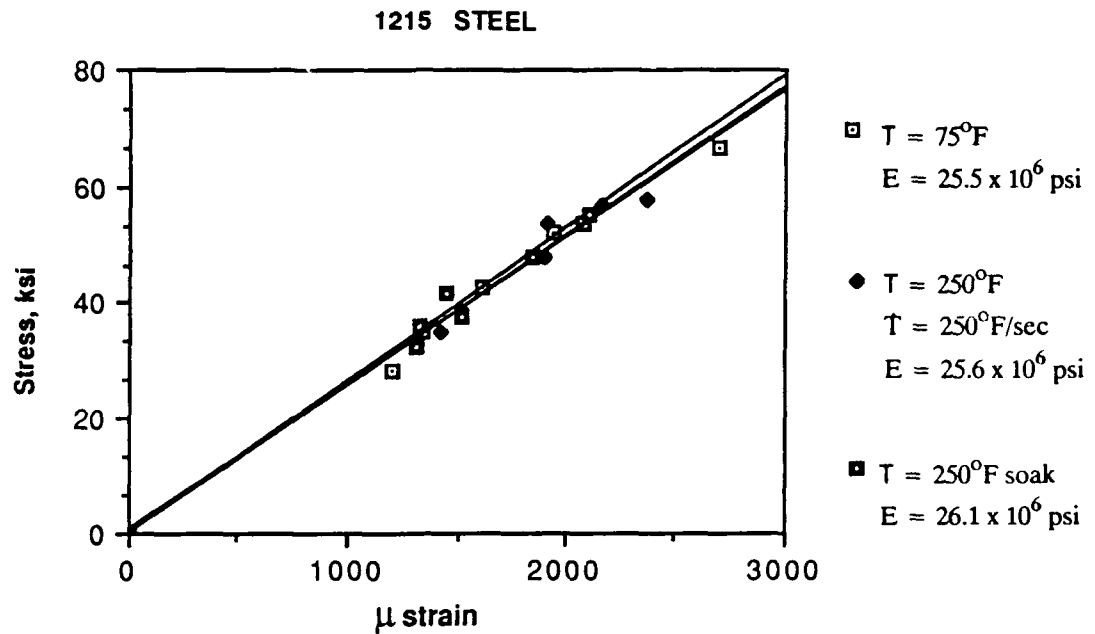


Figure 7. Comparison of speckle results at $\dot{\epsilon} = 10^{-1}/\text{sec}$ and various temperature conditions.

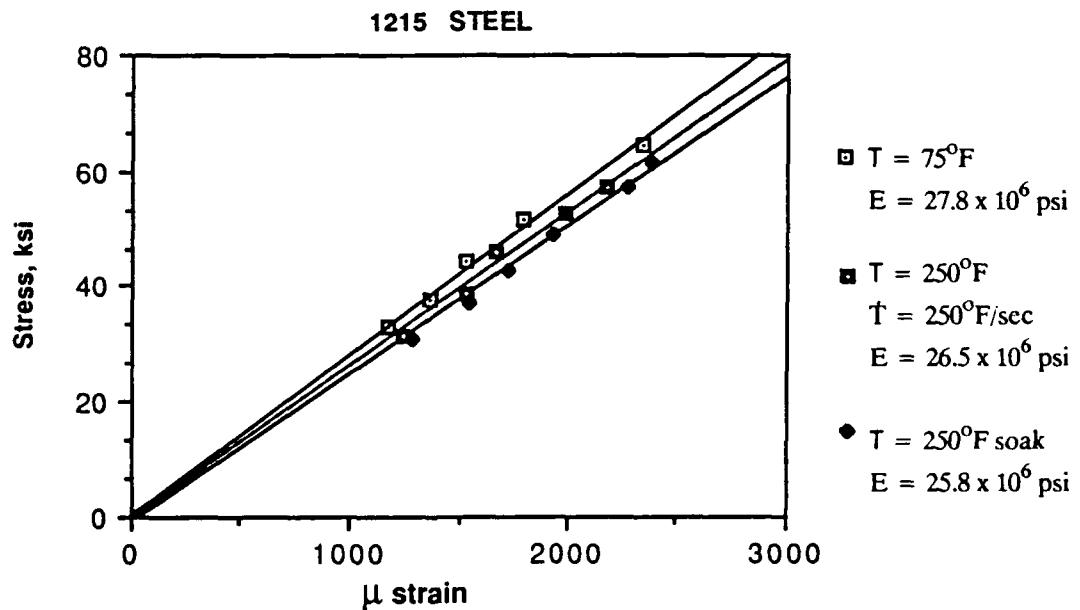


Figure 8. Comparison of speckle results at $\dot{\epsilon} = 10^{-3}/\text{sec}$ and various temperature conditions.

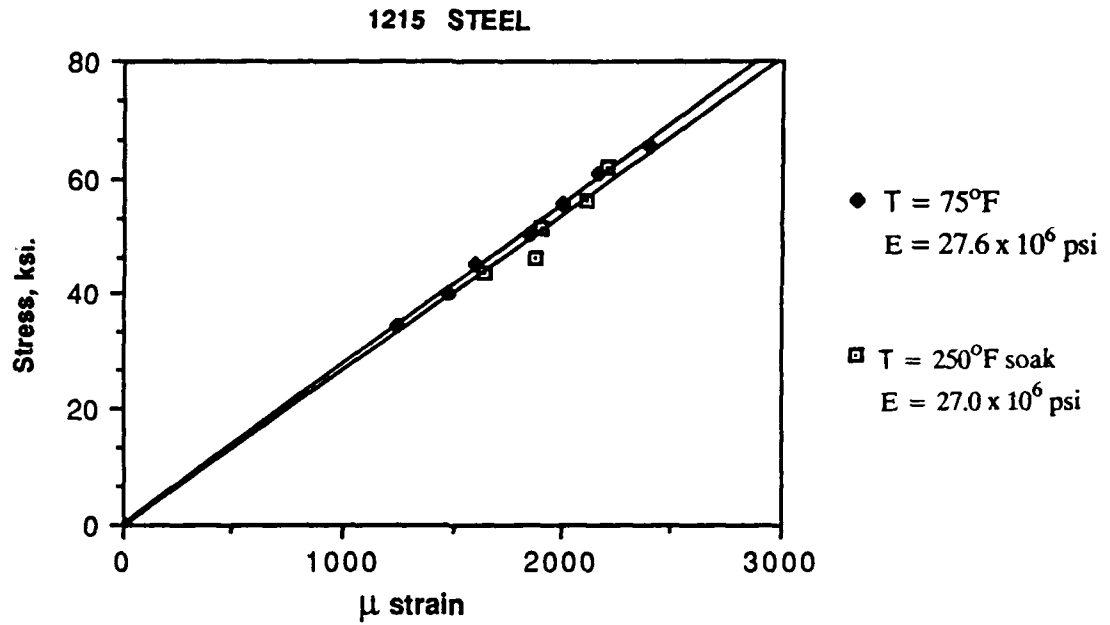


Figure 9. Comparison of speckle results at $\dot{\epsilon} = 10^{-5}/\text{sec}$ and various temperature conditions.

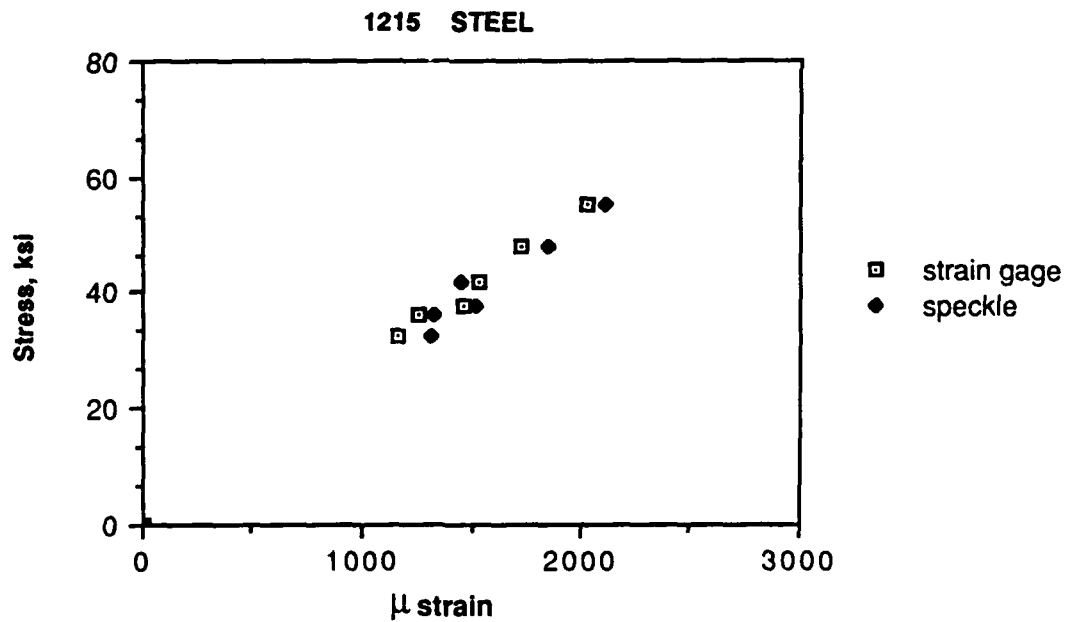


Figure 10. Comparison of speckle and strain gage results for soaking temperature of 250°F and $\dot{\epsilon} = 10^{-1}/\text{sec}$.

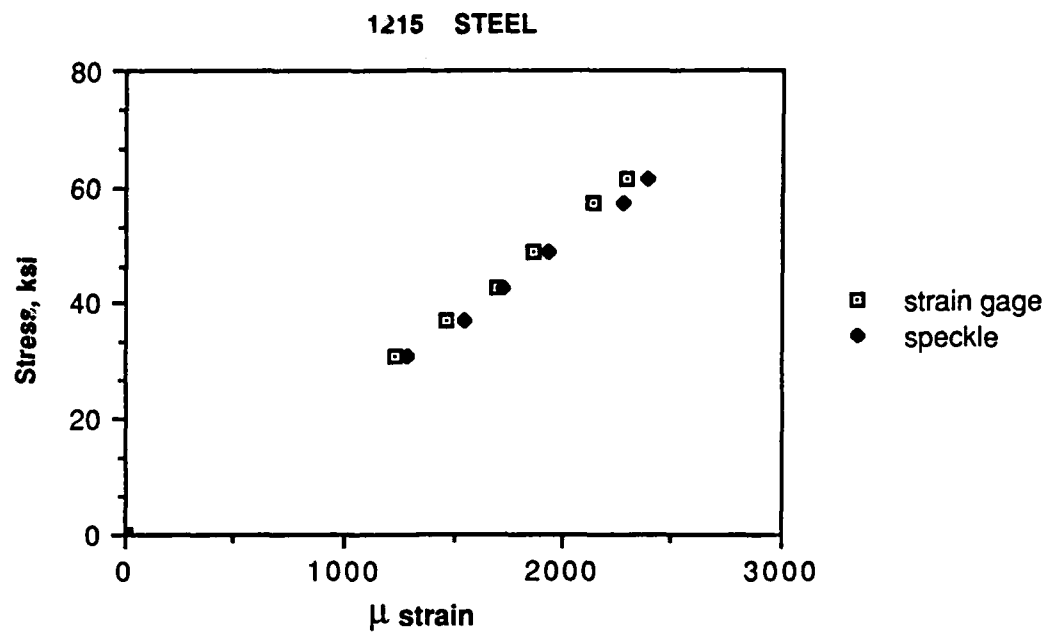


Figure 11. Comparison of speckle and strain gage results for soaking temperature of 250°F and $\dot{\epsilon} = 10^{-3}/\text{sec}$.

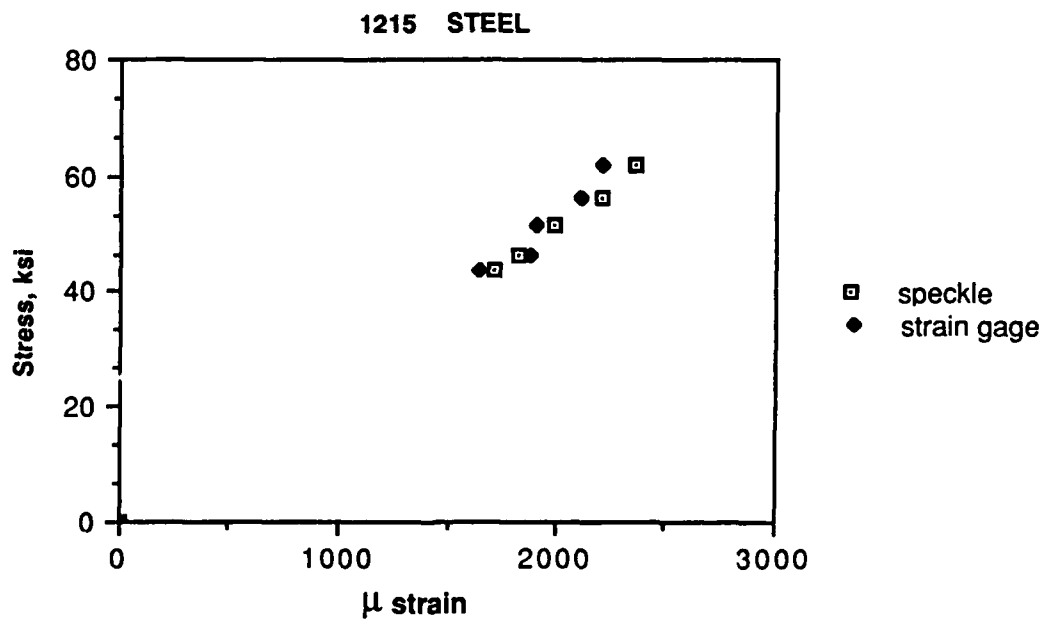


Figure 12. Comparison of speckle and strain gage results for soaking temperature of 250°F and $\dot{\epsilon} = 10^{-3}/\text{sec}$.

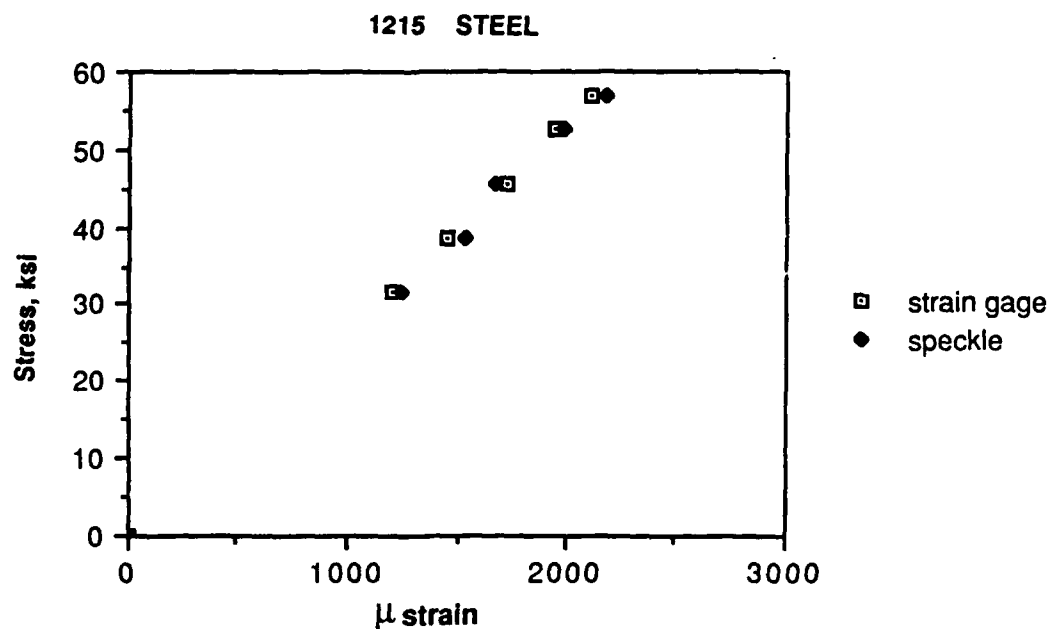


Figure 13. Comparison of speckle and strain gage results at $\dot{\epsilon} = 10^{-3}/\text{sec}$, $T = 250^\circ\text{F}$, and $T = 250^\circ\text{F}/\text{sec}$.

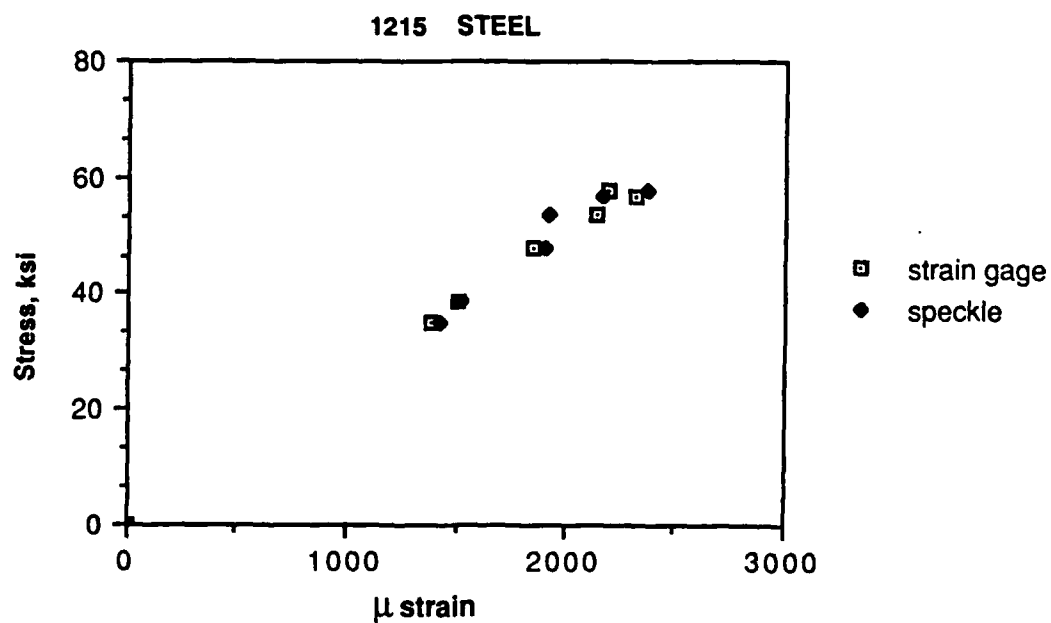


Figure 14. Comparison of speckle and strain gage results at $\dot{\epsilon} = 10^{-1}/\text{sec}$, $T = 250^\circ\text{F}$, and $T = 250^\circ\text{F}/\text{sec}$.

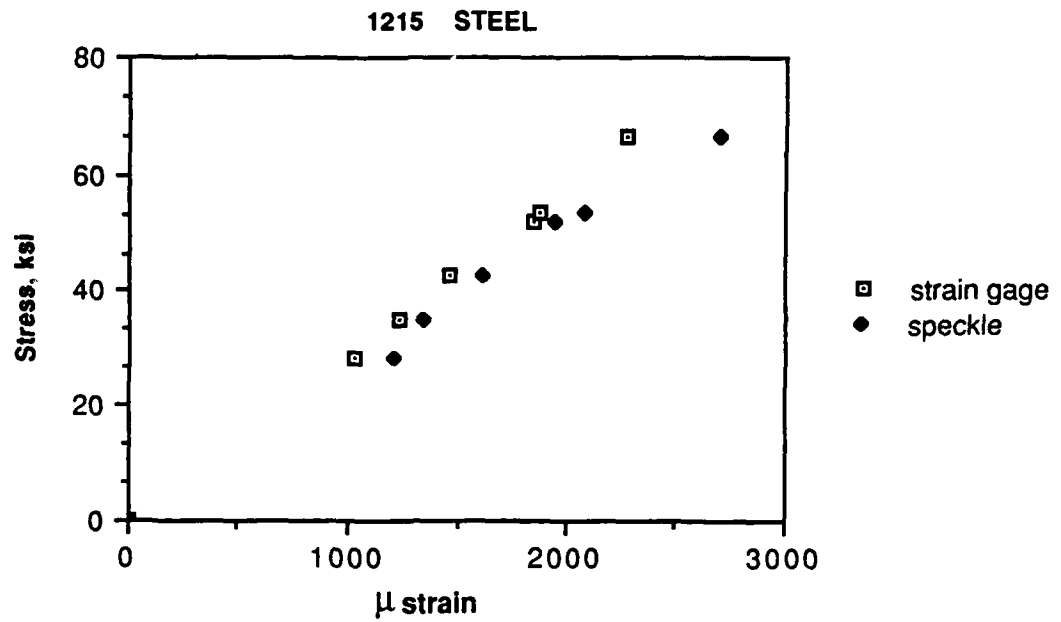


Figure 15. Comparison of speckle and strain gage results at $\dot{\epsilon} = 10^{-1}/\text{sec}$ and $T = 75^\circ\text{F}$.

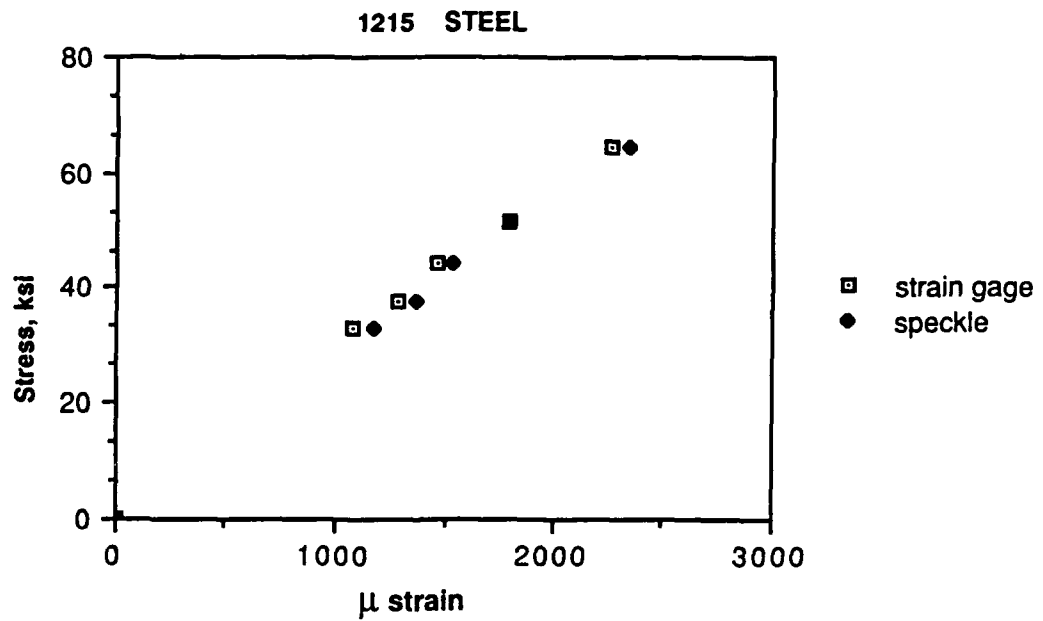


Figure 16. Comparison of speckle and strain gage results at $\dot{\epsilon} = 10^{-3}/\text{sec}$ and $T = 75^\circ\text{F}$.

1215 STEEL

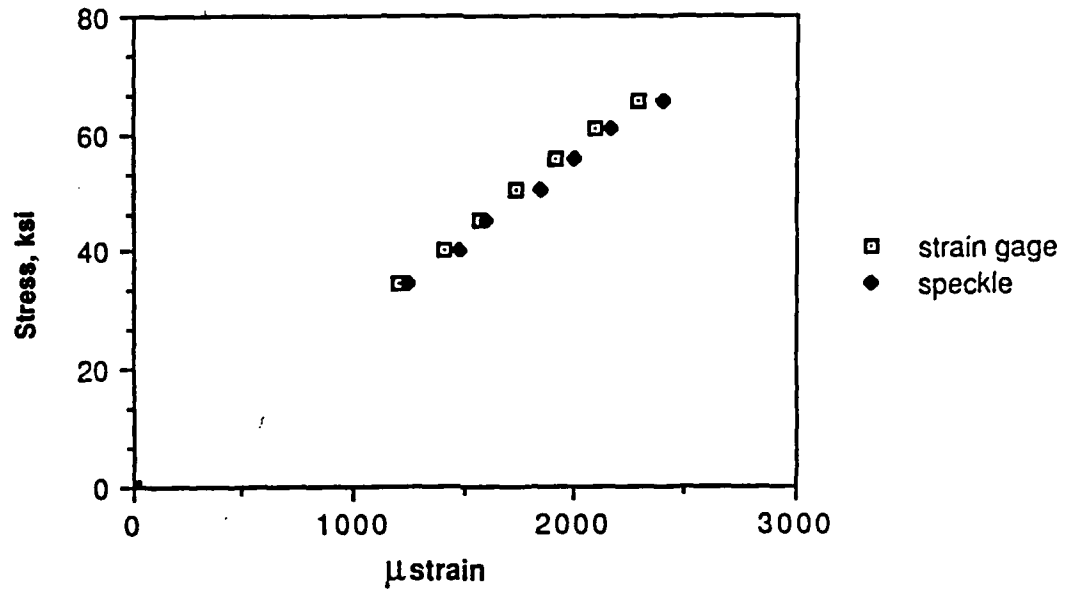


Figure 17. Comparison of speckle and strain gage results at $\dot{\epsilon} = 10^{-5}/\text{sec}$ and $T = 75^\circ\text{F}$.

Aluminum Static Room Temp.

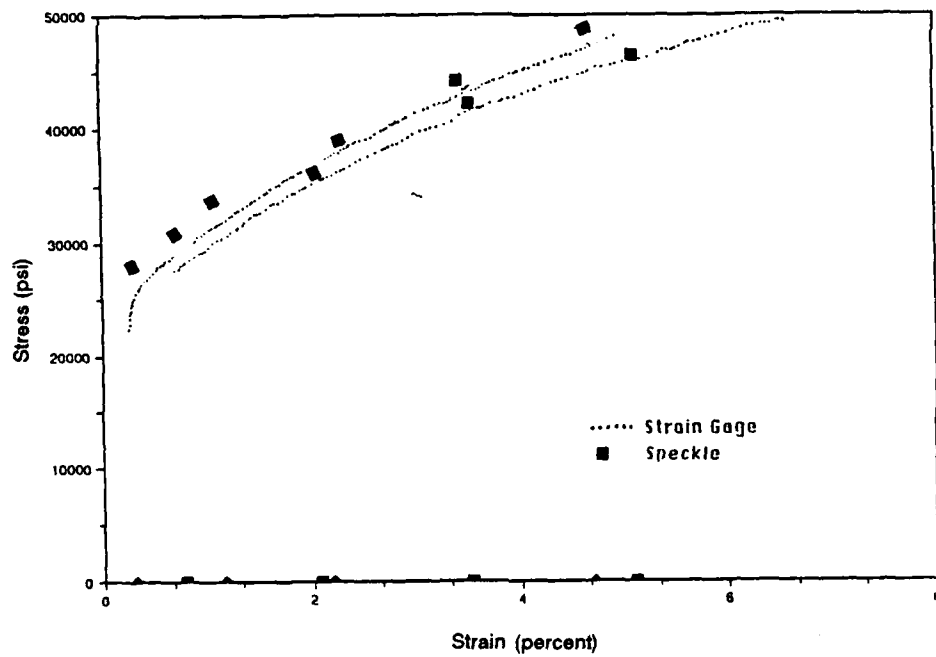


Figure 18. Stress versus strain for aluminum at $\dot{\epsilon} = 10^{-4}$ and $T = 75^\circ\text{F}$.

LSI was used to measure plastic axial strain in aluminum specimens. The results are plotted in Figure 18. The measurements were made up to 5% maximum strain and there was good agreement with strain gage results. Measurements were also made of an aluminum specimen while it was necking. This was done to determine if LSI could be used to measure strain along entire gage length, as well as the necking region only. The results of these experiments and a first order fit of the results, including R, the correlation coefficient, are in Figure 19.

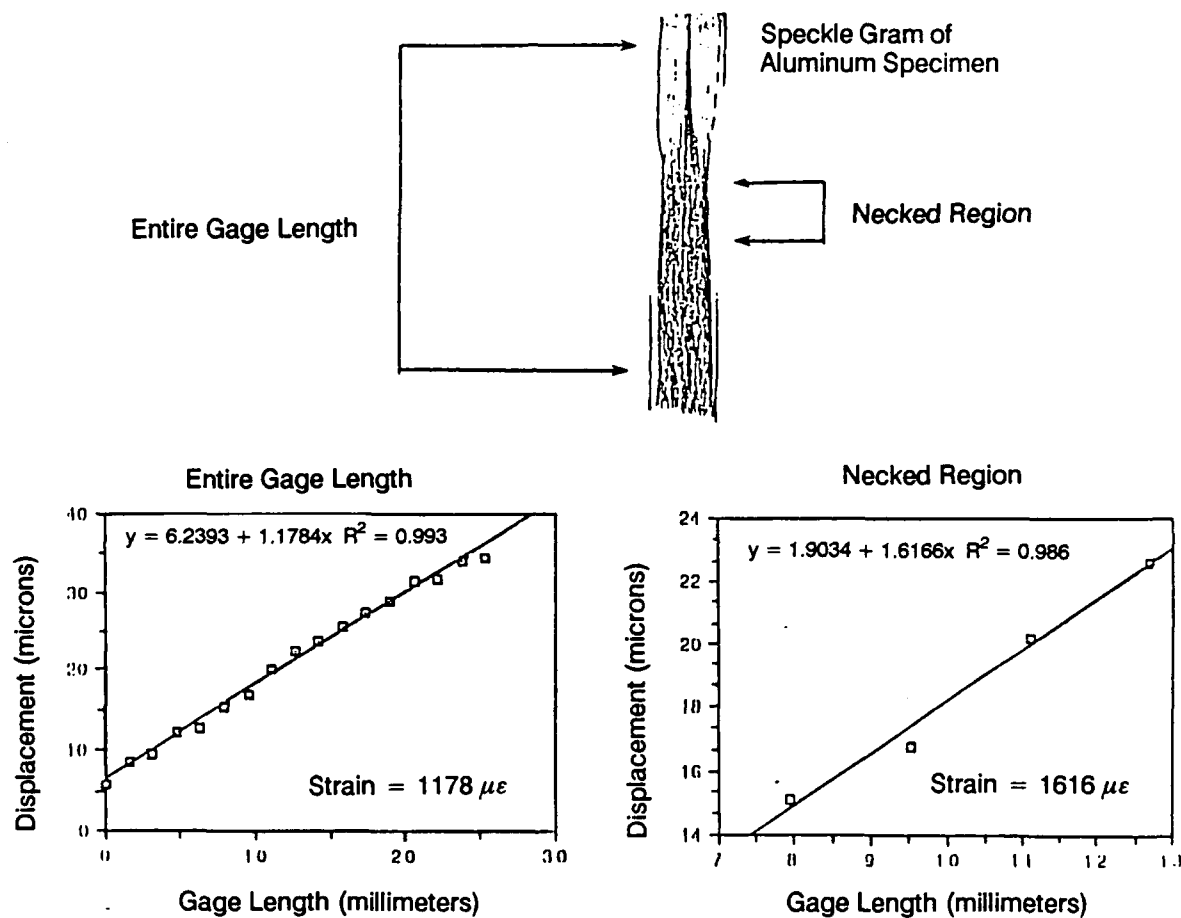


Figure 19. Example of strain measurements in necking region of specimen.

CONCLUSIONS

This study investigated the use of LSI as a method for measuring strain at high temperatures and dynamic loading conditions. Strain was measured at temperatures of 250°F and strain rates up to 10^{-1} /sec. The reason for not going beyond 10^{-1} /sec was due to inherent delays that exist in the ruby laser system. The specimen temperature was limited to 250°F so that strain gages could be used, and strain gage results could be compared with LSI results. Since only one stress-strain data point per specimen can be acquired with the present ruby laser system, to generate a contiguous stress-strain curve, many specimens must be tested under identical conditions. Their results are compiled to form a single stress-strain curve. There are major drawbacks to the present LSI system which incorporates a ruby laser. First, strain rates beyond 10^{-1} /sec cannot be achieved; second, no results can be obtained from a specimen heated to the point where it begins to emit intense red light; and third, for each specimen tested, only one data point is obtained. Although these shortcomings of the present LSI system exist, the LSI system was able to be used to make strain measurements in the necking region. This method of measuring strain could be used to solve the problem of measuring large strains in the necking region of a specimen at high temperatures and dynamic loading conditions if a new laser system is used. The new laser system must have a contiguous beam with a different wave length than red light, a laser chopping system, and a high speed camera with a computer for recording and digitizing film. With a system of that type, LSI could be used to measure large deformations (true stress/true strain) of materials at high temperature and dynamic loading rates.

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U.S. Army Materials Technology Laboratory
Watertown, Massachusetts 02172-0001
THE APPLICATION OF LASER SPECKLE
INTERFEROMETRY TO MEASURE STRAIN
AT ELEVATED TEMPERATURES AND VARIOUS
LOADING RATES - John L. Green, James F. Emslie,
and Shun-Chin Chou
Technical Report MTL TR 90-23, May 1990, 19 pp-
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